Total $\gamma\gamma$ and $\gamma^*\gamma^*$ Cross Sections Measured at LEP

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Recent results on total cross-section measurements in $\gamma\gamma$ and $\gamma^*\gamma^*$ collisions at LEP are reported. Phenomenological fits to the data are presented.

1. Introduction

At LEP2 photon-photon collisions constitute a large part of the inclusive cross-section. Quasi real photons are emitted according to a Weizsäcker-Williams energy spectrum by the lepton beams. Two photon events can be tagged by one or both of the scattered electrons, or anti-tagged, in which case the electrons remain in the beampipe. Tagging detectors measure electrons typically down to 30 mrad. In this paper we report results on anti-tagged (i.e. almost real photon $\gamma\gamma$) and double tagged (i.e. $\gamma^*\gamma^*$) total cross-section measurements. The analyses are based on approximately 390 pb^{-1}, from e^+e^- data taken at $\sqrt{s_{ee}} = 189 - 202$ GeV in '98 and '99.

2. Total $\gamma\gamma$ Cross-Section

Photons at high energies can fluctuate in two-fermion pairs or vector mesons with the same J^{PC} quantum numbers as for the photon. Hence a photon can behave like a hadron, with an additional pointlike component. Total inclusive hadron-hadron cross-sections are known to rise gently with the centre-of-mass (CMS) energy. An outstanding question is whether $\sigma_{\gamma\gamma}$ rises faster than σ_{pp}, expected from the additional pointlike component in the photon structure.

LEP allows to study $\gamma\gamma$ interaction cross-section as function of the CMS energy $W_{\gamma\gamma}$. L3 [1] and OPAL [2] have measured $\sigma_{\gamma\gamma}$ in the region $5 < W_{\gamma\gamma} < 145$ GeV and $10 < W_{\gamma\gamma} < 110$ GeV respectively. The challenge of this measurement is the reconstruction of $W_{\gamma\gamma}$ from the visible hadronic final state. The result depends on the Monte Carlo model used to correct the data: it affects the absolute normalization by approximately 20%, as derived from using two different models, PYTHIA [3] and PHOJET [4]. An important uncertainty is the diffractive contribution to the cross-section. Such events to a large extent escape detection; depending on the model only 6% to 20% of the diffractive events are selected by the standard analysis cuts.

In Fig. 1 data on $\sigma_{\gamma\gamma}$ from the LEP and pre-LEP experiments are shown, compared to various theoretical models as reviewed in [5]. The new L3 data are still preliminary and are a combination of data taken at $\sqrt{s_{ee}} = 189$ and $192 - 202$ GeV [6]. Contrary to previously published data [1], these data are determined using both PHOJET and PYTHIA, and are therefore above published values. The cross-section clearly rises with increasing $W_{\gamma\gamma}$. The OPAL and L3 data are consistent with each other. This is less so for the pre-LEP data [7], of which only a selection is shown in the figure.

All models predict a rise with the collision energy, but the strength of the rise differs and the predictions at high energy show dramatic differences. In *proton-like-models* (dash-dotted [8–10], dashed [11], dotted [12] and solid [13] curves), the curvature follows closely that of proton-proton cross-section, in *QCD based* models (upper [14] and lower [5] bands), the rise is obtained using the pQCD jet cross-section.

A large contribution to the errors of the cross-section is due to the uncertainty of the model dependent correction factors, which are strongly point-to-point correlated and partially hide the

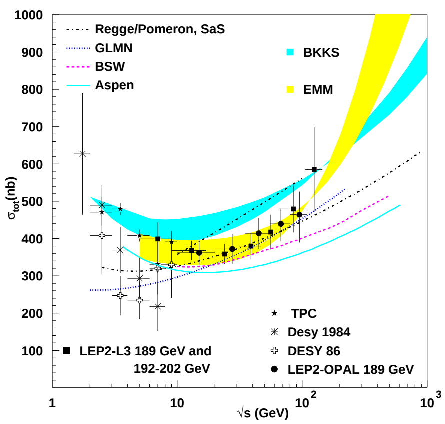

Figure 1. Data on $\sigma_{\gamma\gamma}$, versus $W_{\gamma\gamma}$ (denoted as $\sqrt{s}$) compared with models (see text).

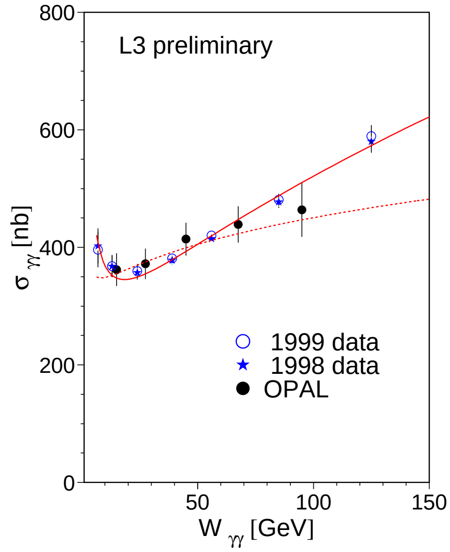

Figure 2. Data on $\sigma_{\gamma\gamma}$ from OPAL and L3, compared with fits through the data (see text).

significance of the rise of the cross-section. Therefore Fig. 2 shows the L3 data without the model dependent errors. The size of the rise is quantified by a Regge inspired fit, $X_1 \cdot s^{\epsilon_1} + Y_1 \cdot s^{-\eta_1}$, i.e. the sum of a pomeron and a Reggeon term. The exponents $\epsilon_1 = \alpha_{I\!P} - 1$ and $\eta_1 = \alpha_R - 1$ are usually assumed to be universal, whereas the coefficients are process dependent. For η_1, which is determined by low energy hadronic data, the value of 0.34 is taken [15]. $\alpha_{I\!P}$ and α_R are the pomeron and Reggeon intercept, respectively.

For its fits, OPAL fixed the coefficient of the Reggeon term, while L3 fitted the magnitude of Y_1. The L3 fit yields for the pomeron term: $\epsilon_1 = 0.263 \pm 0.014$ [6] while OPAL published $\epsilon_1 = 0.101^{+0.025}_{-0.020}$ [2]. The curves show the L3 fits with free (solid line) and fixed (dashed line) value of $\epsilon_1, (\epsilon_1 = 0.095)$. Correlations between the points are taken into account in these fits. L3 observed that the value of ϵ_1 does not depend significantly on the model used for correcting the data. The slope found by OPAL is considerably smaller than the L3 one, despite agreement between the data points. This can be traced back to the assumption on the Regge coefficient, Y_1, which is fixed by OPAL due to absence of its own measurements below $W_{\gamma\gamma} = 10$ GeV to a value of 320 nb. L3 finds $Y_1 \sim 1000$ nb from its own fits. Hence we made fits using the published OPAL and preliminary new L3 data points, ignoring correlations between the points and ignoring the uncertainty due to the model dependence. Refitting the OPAL data but with Y_1 as determined by L3, one finds $\epsilon_1 = 0.205 \pm 0.042$ ($\chi^2/NDF = 1/3$). Refitting all the data, leaving Y_1 free, gives $\epsilon_1 = 0.238 \pm 0.029$ ($\chi^2/NDF = 2.7/9$). Is this rise driven by the point at largest $W_{\gamma\gamma}$ from L3? Removing this point from the fit gives $\epsilon_1 = 0.223 \pm 0.033$, hence no significant change of the exponent.

The corresponding value for ϵ_1 in hadronic collisions is in the range $0.08 - 0.095$, hence the $\gamma\gamma$ cross-section appears to rise significantly faster than hadron cross-sections.

Recently, Donnachie-Landshoff [16] proposed a model which includes two pomeron terms in an attempt to save the universality of the soft pomeron. The total cross-section is then assumed to be described by

$$\sigma = X_1 s^{\epsilon_1} + X_2 s^{\epsilon_2} + Y_1 s^{-\eta_1}, \tag{1}$$

The second pomeron term was added mainly to describe the $\gamma^* p$ data. From fits to pp and $\gamma^{(*)}p$ data the exponents $\epsilon_1 = 0.0808$ $\epsilon_2 = 0.418$ and $\eta_1 = 0.34$ are extracted. An intriguing question is whether the X_2 term is present in the $\gamma\gamma$ data. A fit, as described above, to the preliminary L3 data with $W_{\gamma\gamma} > 20$ GeV, and with two pomerons only, gives $X_2 = 2.5 \pm 0.6$ nb, with $\chi^2/NDF = 4.5/3$. Fitting all OPAL and L3 data to the full expression of eq.(1), keeping the ϵ_1, ϵ_2 and η_1 fixed, gives $X_2 = 5.0 \pm 0.9$ nb, with $\chi^2/NDF = 2.3/9$. Hence, within this model, and within the restrictions of the fits made, the extra hard pomeron term appears to be required in $\gamma\gamma$ data at the 4σ level or higher.

While the cross-section in $\gamma\gamma$ appears to be rising faster than in pp, the γp cross section can be described by a single pomeron term with exponent 0.0808. It is therefore important that the rise in the $\gamma\gamma$ data gets established more thoroughly. This can be accomplished with more and improved cross-section measurements in the high $W_{\gamma\gamma}$ range AND also with better measurements at low $W_{\gamma\gamma}$ from LEP or elsewhere. The latter is important because the fit result depends significantly on the knowledge of the Reggeon term. An experiment at VEPP in Novisibirsk has been scheduled to measure $\sigma_{\gamma\gamma}$ at low $W_{\gamma\gamma}$.

3. Total $\gamma^*\gamma^*$ Cross-Section

The study of virtual photon-photon scattering has recently been discussed as a definite probe of the hard (BFKL) pomeron [17]. The BFKL evolution equation describes scattering processes in QCD in the limit of large energies and fixed, but sufficiently large momentum transfers. The BFKL pomeron has been intensively investigated in the context of small–x deep inelastic electron-proton scattering at HERA. However, despite clear hints [18], the presence of so called $\ln 1/x$ terms in deep inelastic scattering at HERA has not been unambiguously established yet.

The $\gamma^*\gamma^*$ cross-section has been advocated as an excellent measurement to see low-x or so called BFKL effects [19,20]. These measurements can be performed by tagging both scattered electrons, which forces the virtuality of both photons to

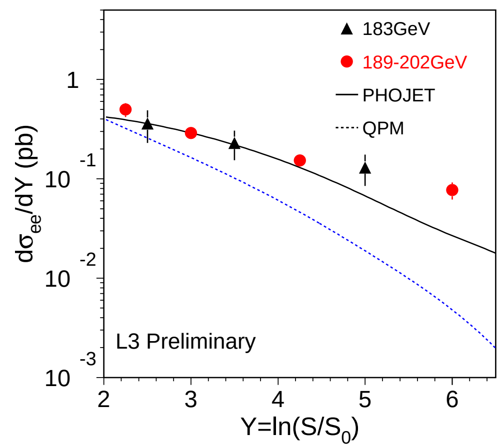

Figure 3. The $ee \to eeX$ cross-section for double tagged events, measured by L3, compared with model predictions (see text).

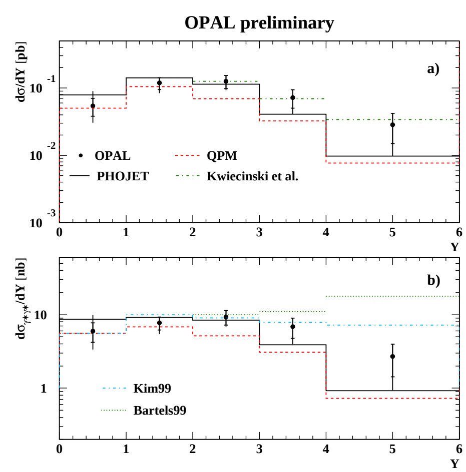

Figure 4. The $\gamma^*\gamma^*$ cross-section, measured by OPAL, compared with model predictions (see text).

be in the multi-GeV region. New measurements from L3 [21] and OPAL [22] of the double tag cross-section are shown as function of the 'length of the gluon ladder Y' in Fig. 3 and Fig. 4. Here $Y = \ln s/s_0$ and $s_0 = \sqrt{Q_1^2 Q_2^2}/(y_1 y_2)$. The measurements are made for the region $34 < \theta_e < 55$ mrad, $E_e > 0.4 E_{beam}$ (OPAL) and 30 mrad $< \theta_e$, $E_e > 40$ GeV (L3), which leads to an average Q^2 of $\langle 17 \rangle$ (OPAL) and $\langle 15 \rangle$ (L3). L3 observes that the cross-section is larger than the QPM and PHOJET 1.05 (which does not contain BFKL) predictions. L3 further fits the $\gamma^*\gamma^*$ cross-section to $\sigma_{\gamma^*\gamma^*} = \sigma_0/\sqrt{Q_1^2 Q_2^2 Y} \cdot (s/s_0)^{\alpha_{I\!P}-1}$, and finds $\alpha_{I\!P} = 0.36 \pm 0.02$, i.e. considerably larger than the pomeron term in $\gamma\gamma$. The OPAL data are above the QPM and PHOJET1.10 predictions, but much less significantly than the L3 data. A possible difference is the sensitivity to radiative corrections of the two measurements [22]. The OPAL measurement was optimized to minimize these effects.

The LO BFKL calculation (Bartels99) is considerably above the data at large Y. Better descriptions are found when NLO corrections are taken into account (Kim99, Kwiecinski et al.) [23,24]. In particular the calculation of [24], which predicts moderate BFKL effects in the LEP region, describes the data well.

4. Conclusion

The total $\gamma\gamma$ cross-section measurements from LEP show an intriguing rise with increasing $W_{\gamma\gamma}$. There is now some evidence that this rise is faster than in hadron-hadron interactions. In $\gamma^*\gamma^*$ scattering there is evidence in the L3 data that the cross-section is above expectation when no BFKL effects are taken into account. The evidence in the OPAL data is broadly consistent with the L3 observation but the significance of the excess over non-BFKL calculations is weaker.

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